Cabin Air Contamination

– An Aeronautical Perspective

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Deutscher Titel: "Kabinenluftkontamination aus technischer Sicht"

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Structured Abstract

**Purpose** – This presentation gives an introduction to aircraft cabin air contamination with an emphasis on contamination due to jet engine oil entering the cabin from the jet engine or auxiliary power unit (APU) via the bleed air system and the air conditioning system. The possible application of sensors and filters is discussed. Filters can be retrofitted. A bleed-free air conditioning architecture, however, seems only financially viable for newly designed aircraft.

**Design/methodology/approach** – The presentation collects existing facts and combines them with own thoughts.

**Findings** – There is a real health and flight safety risk due to contaminated cabin air. For the infrequent flyer the risk is very low. Also aviation statistics are not dominated by cabin air related accidents. Nevertheless, a bleed air based air conditioning system can be regarded as applying a fundamentally wrong systems engineering approach. Measures have to be taken to solve this.

**Research limitations/implications** – This review study is based on references. Own measurements have not been made.

**Practical implications** – The topic has been presented as background information for respiratory physicians.

**Originality/value** – Engineering based information with a critical view on the topic seems to be missing in public. This presentation tries to fill this gap.

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Cabin Air Contamination – An Aeronautical Perspective

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Introduction
MEDICAL INVESTIGATION DAVID LEARMOUNT LONDON

Cabin air killed BA pilot, say experts

Authority on organophosphate poisoning says tissue from Richard Westgate, who died in 2012, “worst case” he has seen

Sustained exposure to organophosphates (OP) from contaminated cabin air contributed to the death of a 43-year-old British Airways pilot, a group of medical experts believe.

Their findings are likely to increase pressure on the industry to take more seriously the issue of sustained exposure to engine bleed air. Airlines and governments have dismissed suggestions that it can be a factor behind flightcrew falling ill.

The pilot, senior first officer Richard Westgate, started flying professionally in 1996 and medical details of his symptoms before death are on record.

Although no coroner’s inquest has been held into his death, medical experts led by Prof Mohamed Abou-Donia of Duke University Medical School, North Carolina, the world’s leading authority on organophosphate poisoning, have just published a study into two autopsies carried out on Westgate, who until his illness was a slim, fit paragliding champion.

Abou-Donia and his colleagues are also investigating the death this year of an unnamed 34-year-old BA airline steward, whose cabin, but they – and aircraft manufacturers – maintain that this is at a harmless level. Abou-Donia argues this was not so in Westgate’s case, despite the fact that the pilot had never logged an actual “fume event” during his career.

WATERSHIP
Frank Cannon, the lawyer acting for the families of both deceased, says the Westgate case is a watershed in this controversy: “They can try explaining one [case] away, but not another and then another.” Cannon says he has “about 50” cases on his books.

(Flight International 2014)
Introduction

... but ...

The Telegraph

By Telegraph Reporters
13 APRIL 2017 • 3:23PM

The family of a British Airways co-pilot who believed he had been poisoned by contaminated cockpit air have accused the airline industry of having its "head in the sand" over the issue.

Richard Westgate, 43, died in December 2012 after moving to the Netherlands to seek help from a specialist clinic for his symptoms which he thought were caused by "aerotoxic syndrome", which has been called "pilot's disease".

A coroner ruled Mr Westgate died accidentally at the Bastion Hotel in Bussum, Netherlands after taking an unintentional overdose of the sleeping tablet pentobarbital.

(Telegraph 2017)

A controversial issue!
Introduction

**Definition: Aircraft Cabin Air**
Aircraft cabin air is the air in the cabin of an aircraft. The air in the cockpit is included in this definition. In pressurized cabins it is the air inside the pressure seals. Pressure control is such that cabin pressure is reduced down to a pressure equivalent to 8000 ft (referring to the ICAO Standard Atmosphere) as the aircraft climbs. In unpressurized aircraft cabins the air is at ambient pressure. Temperature control is done by heating or cooling as required. Venting ensures frequent exchange of cabin air with fresh air from outside. In addition, cabin air can be recirculated and filtered. When flying at high altitudes, cabin air is at similar low relative humidity as the air outside.

**Definition: Quality**
Degree to which a set of inherent characteristics fulfills requirements.

(ISO 9001)
Introduction

**Definition: Contamination**
The process of making a material unclean or unsuited for its intended purpose, usually by the addition or attachment of undesirable foreign substances.

Adapted from (Wiktionary 2018)

The presence of a minor and unwanted constituent (contaminant). Related to health: A harmful intrusion of toxins or pathogens e.g. in food, water, or air.

Adapted from (Wikipedia 2018a)

**Definition: Fume Event** (Rauchereignis)
In a fume event, the cabin and/or cockpit of an aircraft is filled with fume. The fume originates from the bleed air and enters the cabin via the air conditioning system. Air contamination is due to fluids such as engine oil, hydraulic fluid or anti-icing fluid.

Adapted from (Wikipedia 2018b)
**Introduction**

**Definition:** Smell Event (Geruchsereignis)
A fume event without visible fume or smoke, but with a distinct smell usually described as "dirty socks" from the butyric acid originating from a decomposition of the esters that are the base stock of the synthetic jet engine oil.

**Definition (ECA):** Smoke & Fume / Smell Event (cabin air contamination)
An incident may cause only fume, only smell or both. The European Cockpit Association (ECA) explains: "In the context of the ICAO circular [ICAO Circular 344 'Guidelines on Education Training and Reporting Practices related to Fume Events'], fumes and odours are deemed to be synonymous, and the term 'fume(s)' includes both fumes and odours."

(ECA 2018)

**Definition (IATA):** Cabin Air Quality Event (CAQE)
"Cabin air quality events (CAQEs) [are] particularly ... the so-called fume events" (smoke, fumes / odours).  (IATA 2018)
Proposed new Definition:

**Definition: Cabin Air Contamination Event (CACE)**

In a Cabin Air Contamination Event (CACE) the air in the cabin and/or cockpit of an aircraft is contaminated. Sensation of the contamination can be from vison (fume/smoke), olfaction (smell/odor), a combination of typical symptoms experienced by several passengers and/or or crew or by related measurements of CO, CO2, ozon or other "harmful or hazardous concentrations of gases or vapours" (CS-25.831).

<table>
<thead>
<tr>
<th>Headache</th>
<th>Drowsiness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dizziness</td>
<td>Impaired vision</td>
</tr>
<tr>
<td>Nausea</td>
<td>Vomiting</td>
</tr>
<tr>
<td>Tingling</td>
<td>Trembling</td>
</tr>
<tr>
<td>C. hands, etc.</td>
<td>Irritated eyes/throat/nose</td>
</tr>
<tr>
<td>Numbness</td>
<td></td>
</tr>
<tr>
<td>Difficulty</td>
<td>Memory problems</td>
</tr>
<tr>
<td>Muscle</td>
<td></td>
</tr>
<tr>
<td>Breathing</td>
<td>Coughing</td>
</tr>
</tbody>
</table>

Typical Symptoms following a CACE (ECA 2017)
Cabin Comfort and Cabin Air Quality – Health and Flight Safety Implications
Cabin Comfort and Cabin Air Quality – Health and Flight Safety Implications

VOC: Volatile Organic Compounds are (organic chemicals – i.e. including carbon) contained in many products and can be released from these products into the surrounding air. Regulations limit VOCs.

SVOC: Semi-Volatile Organic Compound
Cabin Comfort and Cabin Air Quality – Health and Flight Safety Implications

**Potential Concerns Related to Cabin Air Quality**

<table>
<thead>
<tr>
<th>Concern</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabin Pressure</td>
<td>Can effect people with cardio-respiratory diseases from lack of oxygen</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Temporary drying of skin, eyes, and mucous membranes</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>High concentrations during air-quality incidents. Frequency is believed to be low. CS 25.831: Concentration must be lower than 50 ppm.</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>Concentrations are generally below FAA regulatory limits. Associated with increased perceptions of poor air quality. CS 25.831: Concentration must be lower than 0.5%.</td>
</tr>
<tr>
<td>Ozone</td>
<td>Elevated concentrations on aircraft without ozone converters. Airway irritation and reduced lung function. CS 25.832: Concentration &lt; 0.25 ppm resp. 0.1 ppm.</td>
</tr>
<tr>
<td>Pesticides</td>
<td>From aircraft “disinsection” with pesticides.</td>
</tr>
<tr>
<td>Engine Oil</td>
<td>Fumes from hot engine oil may enter the cabin via the bleed air system.</td>
</tr>
<tr>
<td>Hydraulic Fluids</td>
<td>Frequency of incidents is expected to be relatively low. Mild to severe health effects.</td>
</tr>
<tr>
<td>Deicing Fluid</td>
<td>Hazardous substance. Skin sensitizing and irritant.</td>
</tr>
<tr>
<td>Airborne Allergens</td>
<td>Exposure frequency is not known. Irritated eye and nose; sinusitis; acute increases of asthma; possible anaphylaxis.</td>
</tr>
<tr>
<td>Nuisance Odors</td>
<td>Can be present on any flight.</td>
</tr>
</tbody>
</table>

Adapted from (NRC 2002)
## Cabin Comfort and Cabin Air Quality – Health and Flight Safety Implications

<table>
<thead>
<tr>
<th>Potential sources of cabin air contamination</th>
<th>Potential impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine start during push back</td>
<td>Exhaust gases (e.g., CO, CO₂, NOₓ, fuel, particles)</td>
</tr>
<tr>
<td>Bleed air switch off during engine start</td>
<td>Short time increase of CO₂</td>
</tr>
<tr>
<td>Cabin cleaning in general</td>
<td>VOC, e.g. alcohols, flavors (terpenes), aldehydes</td>
</tr>
<tr>
<td>Interior cleaning</td>
<td>Residual of tetrachloroethene</td>
</tr>
<tr>
<td>No ozone converters installed</td>
<td>Ozone, particularly in cruise</td>
</tr>
<tr>
<td>De-icing fluids</td>
<td>1,2-Propanediol (major constituent) and various additives (e.g., dyes, thickener, antioxidants)</td>
</tr>
<tr>
<td>Aircraft traffic at the airport</td>
<td>Exhaust gases (e.g., CO, CO₂, NOₓ, fuel, particles)</td>
</tr>
<tr>
<td>Car traffic at the airport</td>
<td>Exhaust gases (e.g., CO, CO₂, NOₓ, gasoline, particles)</td>
</tr>
<tr>
<td>Passengers</td>
<td>Emission of CO₂, various VOCs, offensive smell</td>
</tr>
<tr>
<td>Restrooms</td>
<td>Smell, VOC from cleaning products</td>
</tr>
<tr>
<td>Furnishings</td>
<td>VOC/SVOC, particulate organic matter (POM), flame retardants e.g. organophosphates</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Various VOCs, lubricants</td>
</tr>
<tr>
<td>Lubricants</td>
<td>Oil base stock, organophosphates, POM</td>
</tr>
<tr>
<td><strong>Hydraulic fluids</strong></td>
<td>e.g. Tributyl phosphate (TBP), triphenyl phosphate (TPP)</td>
</tr>
<tr>
<td><strong>Engine oils</strong></td>
<td>Tricresyl phosphate (TCP), trixylyl phosphate (TXP), Amines</td>
</tr>
<tr>
<td><strong>In case of thermal degradation</strong></td>
<td>VOCs, organic acids, aldehydes, CO, CO₂, potential unknown products</td>
</tr>
</tbody>
</table>

*(EASA 2017a)*
Cabin Comfort and Cabin Air Quality – Health and Flight Safety Implications

**Health Effects:** Occupational Health & Flight Safety

may be experienced soon after exposure or, possibly, years later:

- **Long-term health effects:**
  - to passengers
  - to crew => **occupational health** (OH)
  - usually related to
  - Time-Weighted Average (TWA)
  - Permissible Exposure Limits (PEL) => CS 25.831

- **Immediate health effects:**
  - to passengers
  - to cabin crew
  - to cockpit crew => **flight safety implications** can lead to:
  - injury or death of
  - passenger
  - crew => CS 25.1309

(Eurofins 2017, EASA CS-25)
Cabin Comfort and Cabin Air Quality – Health and Flight Safety Implications

Occupational Health – Long Term Health Effects

EASA CS-25: CS 25.831 Ventilation
(a) Each passenger and crew compartment must be ventilated ... to enable crewmembers to perform their duties without undue discomfort or fatigue.
(b) Crew and passenger compartment air must be free from harmful or hazardous concentrations of gases or vapours. In meeting this requirement, the following apply: (1) Carbon monoxide concentrations in excess of one part in 20000 parts of air [50 ppm] are considered hazardous. For test purposes, any acceptable carbon monoxide detection method may be used. (2) Carbon dioxide concentration ...

"EASA is of the opinion ... only applicable for ... CO and CO2"
Remark: EASA’s interpretation of certification rules: The cabin is allowed to be contaminated with other substances!

"The BFU is of the opinion that 'harmful concentration' should be interpreted ... to mean that health impairments (including long-term) through contaminated cabin air should be eliminated."

"The BFU is of the opinion that a product [aircraft] which has received a type certificate by EASA should be designed in a way that neither crew nor passengers are harmed or become chronically ill."

(BFU 2014)
Flight Safety Implications – Immediate Health Effects

There have been several (much debated) critical flight instances, but so far (luckily) no death (due to flight safety implications) and no hull loss.

Compare e.g. with the issue "Degraded Manual Flying Skills" (Flight International 2017)

<table>
<thead>
<tr>
<th>Year</th>
<th>Operator</th>
<th>Type</th>
<th>Location</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Egyptair</td>
<td>Airbus A320</td>
<td>Mediterranean Sea off Egypt</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>Flydubai</td>
<td>Boeing 737-800</td>
<td>Rostov-on-Don, Russia</td>
<td>62</td>
</tr>
<tr>
<td>2014</td>
<td>AirAsia Indonesia</td>
<td>Airbus A320</td>
<td>Java Sea, Indonesia</td>
<td>162</td>
</tr>
<tr>
<td>2013</td>
<td>Swiftair</td>
<td>Boeing MD-83</td>
<td>Mali</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td>Tatarstan Air</td>
<td>Boeing 737-500</td>
<td>Kazan, Russia</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Asiana Airlines</td>
<td>Boeing 777</td>
<td>San Francisco, USA</td>
<td>___</td>
</tr>
<tr>
<td>2010</td>
<td>Afriqiyah Airways</td>
<td>Airbus A330-200</td>
<td>Tripoli, Libya</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>Ethiopian Airlines</td>
<td>Boeing 737-800</td>
<td>Near Beirut, Lebanon</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Yemenia</td>
<td>Airbus A310-200</td>
<td>Comoros Islands</td>
<td>152</td>
</tr>
<tr>
<td></td>
<td>Air France</td>
<td>Airbus A330-300</td>
<td>South Atlantic</td>
<td>228</td>
</tr>
<tr>
<td>2009</td>
<td>Caspian Airlines</td>
<td>Tupolev Tu-154</td>
<td>Iran</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>Colgan Air</td>
<td>Bombardier Q400</td>
<td>Buffalo, New York, USA</td>
<td>49</td>
</tr>
<tr>
<td>2008</td>
<td>Aeroflot Nord</td>
<td>Boeing 737-500</td>
<td>Perm, Russia</td>
<td>88</td>
</tr>
<tr>
<td>2007</td>
<td>Adam Air</td>
<td>Boeing 737-400</td>
<td>Java Sea, Indonesia</td>
<td>102</td>
</tr>
<tr>
<td>2006</td>
<td>Armavia</td>
<td>Airbus A320-200</td>
<td>Sochi, Russia</td>
<td>113</td>
</tr>
<tr>
<td>2005</td>
<td>West Caribbean</td>
<td>Boeing MD-82</td>
<td>Venezuela</td>
<td>160</td>
</tr>
<tr>
<td>2004</td>
<td>Flash Airlines</td>
<td>Boeing 737-300</td>
<td>Sharm el-Sheikh, Egypt</td>
<td>148</td>
</tr>
<tr>
<td>2000</td>
<td>Gulf Air</td>
<td>Airbus A320-200</td>
<td>Bahrain</td>
<td>143</td>
</tr>
<tr>
<td></td>
<td>Crossair</td>
<td>Saab 340</td>
<td>Near Zurich, Switzerland</td>
<td>10</td>
</tr>
</tbody>
</table>

From 2000 to 2017:
- 19 fatal accidents
- 2012 fatalities

Remark:
There are certainly several issues in aviation of more pressing nature than "cabin air quality / contamination", however, the suffering of individuals (potentially / probably) due to cabin air contamination can not be ignored (may it just be for ethical reasons), because the underlying deficits in aircraft system design are a fact (see below) and need to be solved.
Jet Engine Oil
Jet Engine Oil

**warning:** contains TCP tricresylphosphate. Swallowing this product can cause nervous system disorders, including paralysis. Prolonged breathing of oil mist, or prolonged or repeated skin contact can cause nervous system effects.

This warning was changed in 2004 (Michaelis 2012) to:

"This product is not expected to produce adverse health effects under normal conditions of use ... Product may decompose at elevated temperatures ... and give off irritating and/or harmful ... gases/vapours/fumes. Symptoms from acute exposure to these decomposition products in confined spaces [aircraft cabin] may include headache, nausea, eye, nose, and throat irritation."

(Exxon 2016c)

Judging Jet Engine Oil Based on Warnings Given by Manufacturer

Material Safety Data Sheet (MSDS)

**FIRST AID MEASURES, INHALATION**
Remove from further exposure [in a fume event?]... Use adequate respiratory protection [not available for passengers!]. If respiratory irritation, dizziness, nausea, or unconsciousness occurs, seek immediate medical assistance. If breathing has stopped, assist ventilation with a mechanical device or use mouth-to-mouth resuscitation.

(Exxon 2016c)
Jet Engine Oil

**Tricresyl Phosphate (TCP)**

- **TOCP**: ortho-cresyl group containing molecules are highlighted in **bold**, they are the **toxic** isomers.

- **OC**: ortho-cresyl group
- **MC**: meta-cresyl group
- **PC**: para-cresyl group

**Formulas**:

- **TOCP**: \[
\begin{array}{c}
\text{CH}_3 \\
\text{CH}_3 \\
\text{H}_3\text{C} \\
\end{array}
\]
- **DOCP**: \[
\begin{array}{c}
\text{CH}_3 \\
\text{H}_3\text{C} \\
\end{array}
\]
- **MOCP**: \[
\begin{array}{c}
\text{CH}_3 \\
\end{array}
\]

**Notation**:

- **T** = tri (3)
- **D** = di (2)
- **M** = mono (1)

(Winder 2001)
Jet Engine Oil

TCP Toxicity Basics

Winder 2001 / Henschler 1958

- The **10 isomers** that make up TCP are toxicologically different.
- The ortho containing isomers are toxic, without ortho isomers are not toxic (Henschler 1958).
- Most infamous and most studied: TOCP (tri-ortho-cresyl phosphate).
- Other ortho containing isomers in TCP are **more neurotoxic than TOCP**:
  - DOCP (di-ortho-cresyl phosphates): 5 times more neurotoxic ($TEF = 5$),
  - MOCP (mono-ortho-cresyl phosphates): 10 times more neurotoxic ($TEF = 10$).

- DOCP and MOCP are present in the engine oil in **higher concentration** than TOCP.
- Based on **concentration** ($C_i$ in ppm) and **relative neurotoxicity** (toxic equivalency factor, $TEF$) for each isomer an **equivalent TOCP toxicity** ($TEQ$) can be calculated. The base unit of the equivalent TOCP toxicity is proposed to be that of 1 ppm ($\approx$1mg/l) of TOCP in the oil. $TEQ = \sum C_i \cdot TEF_i$.
- Winder calculates this **equivalent TOCP toxicity**, considering the presents of all ortho isomers:
  - TEQ for Mobil Jet Oil II: 30730
  - (The TEQ of this oil would be less than 1 if only TOCP would be present and no other ortho isomers! Therefore, ignoring the DOCP and MOCP content of the oil yields highly inaccurate results.)
  - TEQ for Mobil 291: 17606
Jet Engine Oil

TCP Toxicity Basics

Henschler 1958
- TCP toxicity is found from animal poisoning with hens and cats.
- Results obtained from these test animals can be applied to humans (with caution).
- TOCP acts on the peripheral nerves and causes predominantly atonic peripheral paralysis.
- MOCP and DOCP act rather on the brain and on the spinal cord. This leads to spastic paralysis.
- If the content of TOCP, DOCP, and MOCP is known, calculation of TEQ is directly possible (see previous page).
- If only the total ortho cresyl (OC) content $q$ in the TCP is known, the toxic equivalency factor, $TEF$ can be calculated based on a purely statistical distribution of the 10 isomers (as Henschler shows). It is easy to understand:
  - At 0% of OC neither of MOCP, DOCP, nor TOCP are present: $TEF = 0$
  - At 100% of OC only TOCP would be present and $TEF = 1$ by definition.
- The theoretical formula (blue) is with $TEF$(TOCP) = 1:
  $$TEF = 16q^3 - 45q^2 + 30q$$
- According to Henschler this curve needs to be adapted to fit his experimental results (red). An equation to fit this experimental curve would be (purple):
  $$TEF = 330q^2$$  \text{valid for } q < 0.13
- and can be applied to typically low OC content.
Jet Engine Oil

Manufacturer Specified Jet Engine Oil Content and Toxicity

SAFETY DATA SHEET (MSDS) MOBIL JET OIL II (Exxon 2016c)

Synthetic Esters and Additives

<table>
<thead>
<tr>
<th>Name</th>
<th>CAS#</th>
<th>Concentration*</th>
<th>GHS Hazard Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-PHENYL-1-NAPHTHYLAMINE</td>
<td>90-30-2</td>
<td>1%</td>
<td>H302, H317, H400(M factor 1), H410(M factor 1)</td>
</tr>
<tr>
<td>ALKYLATED DIPHENYL AMINES</td>
<td>68411-46-1</td>
<td>1 - &lt; 5%</td>
<td>H402, H412</td>
</tr>
<tr>
<td>TRICRESYL PHOSPHATE</td>
<td>1330-78-5</td>
<td>1 - &lt; 3%</td>
<td>H361(F), H400(M factor 1), H410(M factor 1)</td>
</tr>
</tbody>
</table>

Exxon fails to specify the ortho Cresyl (OC) concentration of the oil. Exxon only uses the CAS# for the mixed isomers, as such hiding information.

H302: Harmful if swallowed
H317: May cause allergic skin reaction
H361(F): Suspected of damaging fertility
H400: Very toxic to aquatic life, H402: Harmful to aquatic life
H410: Very toxic to aquatic life with long lasting effects, H412: Harmful to aquatic life with long lasting effects

Remark:
According to the stated Health Hazards of Mobil Jet Oil II and the information in Michaelis 2010 (p. 67), the ortho content must be less than 0,2% in the oil (6,7% in the TCP) otherwie instead of the "harmful" declaration a "toxic" decalration would be mandatory. But with q = 6,7%, TEF = 1,47 and hence the TCP may still be more toxic than pure TOCP under the given hazard declaration!
Jet Engine Oil

**Actual OCP Content of the TCP --- Isomerization**

**Ramsden 2013a**
OC content in the TCP:
TCP Class 1: 30% (about 1930)
TCP Class 2: ?
TCP Class 3: 3% (about 1958, "modern TCP")
TCP Class 4: 0.3 % (since 1992, "conventional TCP")
TCP Class 5: \( \approx 0.03 \% \) (since 1997, "low-toxicity TCP")

TCP Class 6: 0 % (since 2017, "zero-OCP TCP")  Remark / Introduction: Proposal for a new class definition

**Ramsden 2013 / Imbert 1997**
Another possibility is that isomerization of the TCP takes place within the engine during operation.

**Megson 2016**
... temperatures of 400 °C. These temperatures have the potential to alter the composition of the original oil and create other toxic compounds.

There is currently a large degree of uncertainty as to what compounds are produced and how toxic they are through inhalation in the vapour phase at high altitudes.
Jet Engine Oil

**Actual OCP Content Measured**

A comparison of fresh and used aircraft oil for the identification of toxic substances ...

(Megson 2016)

<table>
<thead>
<tr>
<th>CAS #</th>
<th>[M⁺] m/z</th>
<th>Formula</th>
<th>Concentration in oil (%)</th>
<th>Fresh oil 1</th>
<th>Fresh oil 2</th>
<th>Fresh oil 3</th>
<th>Used oil 1</th>
<th>Used oil 2</th>
<th>Used oil 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ooc-TCP</td>
<td>1330-78-5</td>
<td>C₂₃H₂₁PO₄</td>
<td>0.68</td>
<td>0.70</td>
<td>0.70</td>
<td>0.40</td>
<td>0.52</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>oom-TCP</td>
<td>368.118</td>
<td>C₂₃H₂₁PO₄</td>
<td>1.51</td>
<td>2.01</td>
<td>1.58</td>
<td>1.05</td>
<td>1.16</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>oop-TCP</td>
<td>368.118</td>
<td>C₂₃H₂₁PO₄</td>
<td>1.21</td>
<td>1.42</td>
<td>1.39</td>
<td>0.78</td>
<td>0.97</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>omm-TCP</td>
<td>368.118</td>
<td>C₂₃H₂₁PO₄</td>
<td>0.45</td>
<td>0.55</td>
<td>0.53</td>
<td>0.22</td>
<td>0.26</td>
<td>0.24</td>
<td></td>
</tr>
</tbody>
</table>

Summation of TPC (%): 4.85 4.68 4.20 2.45 2.91 2.92

No tri-ortho cresyl phosphate **TOCP** isomers were detected.
No di-ortho cresyl phosphate **DOCP** isomers were detected.
No mono-ortho cresyl phosphate **MOCP** isomers were detected.

TCP Class 6: No OCP Content (2016)
EASA Study 2017: AVOIL (EASA 2017b)

AVOIL – Characterisation of the toxicity of aviation turbine engine oils after pyrolysis

"From the experimental work on detecting chemicals it is concluded that the commercial oils included in this study do contain TCP, however no tri-ortho cresyl phosphate [TOCP] isomers could be detected. Remark: The content of DOCP and MOCP is not mentioned.

A list of 127 compounds [VOC] was identified ...
(For hazard profile see Appendix 6 of EASA 2017b. See Remark 3 below.)

Analysis of the human sensitivity variability factor showed that the complete metabolic pathway and the contribution of inter individual variability in the metabolic enzymes is still largely unknown for the majority of industrial chemicals, ...

Based on the study on toxic effects of the oils after pyrolysis it was concluded that the current data indicate that neuroactive pyrolysis products are present, ...

... but that their concentration in the presence of an intact lung barrier is that low that it could not be appointed as a major concern for neuronal function."

Remarks / Questions:
1.) No more TOCP. Good, but DOCP and MOCP were not in the focus. This could be misleading.
2.) What about people with deficits in their lung barrier functionality?
3.) "not ... a major concern for neuronal function" drawn too quick in view of the 127 compounds found, many with their individual hazards and possible interaction and their effect on humans.
How much Oil Gets into the Cabin?

**EASA Study 2017: AVOIL (EASA 2017b)**

**AVOIL – Characterisation of the toxicity of aviation turbine engine oils after pyrolysis**

"a ... list of 127 compounds [VOC] was ... identified ... ". The hazard profile is given in Appendix 6:

<table>
<thead>
<tr>
<th>Compound #</th>
<th>Name</th>
<th>CAS</th>
<th>Harmonized classification</th>
<th>Self-classification*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diethyl Phthalate</td>
<td>84-66-2</td>
<td></td>
<td>NC</td>
</tr>
<tr>
<td>2</td>
<td>1-Nonene, 4,6,8-trimethyl-</td>
<td>54410-98-9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2-Ethylhexyl salicylate</td>
<td>118-60-5</td>
<td></td>
<td>Skin Irrit. 2</td>
</tr>
<tr>
<td>4</td>
<td>Acetophenone</td>
<td>98-86-2</td>
<td>Acute Tox. 4</td>
<td>Eye Irrit. 2</td>
</tr>
<tr>
<td>5</td>
<td>Benzaldehyde</td>
<td>100-52-7</td>
<td>Acute Tox. 4</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Benzene, 1,3-bis(1,1-dimethylethyl)-</td>
<td>1014-60-4</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>7</td>
<td>Heptane, 4-methyl-</td>
<td>589-53-7</td>
<td>Asp. Tox. 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Skin Irrit. 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STOT SE 3</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Nonanal</td>
<td>124-19-6</td>
<td></td>
<td>NC</td>
</tr>
<tr>
<td>9</td>
<td>2,4-Dimethyl-1-heptene</td>
<td>19549-87-2</td>
<td>Asp. Tox. 1</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Decanal</td>
<td>110-21-2</td>
<td></td>
<td>Eye Irrit. 2</td>
</tr>
<tr>
<td>124</td>
<td>Isopropyl myristate</td>
<td>110-27-0</td>
<td></td>
<td>NC</td>
</tr>
<tr>
<td>125</td>
<td>Tetradecanoic acid</td>
<td>544-63-8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>126</td>
<td>1-Pentene, 4-methyl-</td>
<td>691-37-2</td>
<td>Asp. Tox. 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Or</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Skin Irrit. 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Eye Irrit. 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STOT SE 3</td>
<td></td>
</tr>
<tr>
<td>127</td>
<td>2-Cyclopenten-1-one</td>
<td>930-30-3</td>
<td></td>
<td>NC</td>
</tr>
</tbody>
</table>

* according to the largest number of notifiers
NC = not classified for human health effects
NR = not registered under REACH
Air Conditioning Technology
Air Conditioning Technology

Air Conditioning Basics

Increasing Temperature of Air due to Compression from Ambient to Cabin Pressure

1) compress the air => increasing temperature of air
2) cool the air
Air Conditioning Technology

Air Conditioning Basics
Temperature Control, Pressure Control, Ventilation

1) compress the air
2) cool the air
=> Temperature Control

3) release the air
=> Pressure Control:
out > in: pressure goes down
in > out: pressure goes up

Adapted from (NRC 2002)
Air Conditioning Technology

Air Conditioning with Recirculation

Adapted from (NRC 2002)
"Bleed Air" Generation and Treatment

compress and cool the air

"Bleed Air" is "precious air" taken off the engine compressor – air which was initially intended to be used for the engine cycle.

Adapted from (A340 FCOM)
2b) Air Cooling

Temperature Control (i)

Adapted from (FCOM A320)
Cabin Air Distribution

A320

- Ceiling outlet
- Crew individual outlets
- Flow control for windshield outlets
- Windscreen outlet
- Crew individual outlets
- Side window outlet
- Flow control
- Avionic emergency supply
- Supply duct
- Cabin outlets
- Cabin ambient air to underfloor area

(A320 GENFAM)
Major Component Location

Air Conditioning Technology

737-600/700/800/900 AIRCRAFT MAINTENANCE MANUAL

Dieter Scholz:
Cabin Air Contamination

59th Congress of the
German Respiratory Society

16.03.2018, Slide 35
Aircraft Design and Systems Group (AERO)
Air Conditioning Technology

Air Conditioning Pack (1/2)
A320
Air Conditioning Technology

Air Conditioning Pack (2/2)

- An **Air Cycle Machine (ACM)** is a high energy rotor device.
- An ACM may need some form of lubrication (=> oil)
- Lubrication needs will be much smaller than in aircraft engines or the APU.
- Use of air bearings is possible.

(A320 AMM)
Air Conditioning Technology

**SAE about the Design of the Air Conditioning Pack**

**SAE ARP 85E: Air Conditioning Systems for Subsonic Airplanes**

5.2.2.d.: Bearings:

Air cycle machines typically use precision angular contact ball bearings or air bearings.

In either case, the bearing system should be self-contained, requiring no external oil supply or external pressurizing air source.
Jet Engine
Engine Overview

Jet Engine

(Wikipedia 2017a)
Jet Engine

Jet Engine Bearing

(Exxon 2016b)
Jet Engine

Engine Air and Oil System

Normal operation of engine seals:
1. The "drain" discharges **oil**.
2. The "dry cavity" contains **oil**.
3. Air and **oil** leak from bearings **into** the **bleed air**.

=> Engines leak small amounts of oil by design!

based on (Exxon 2016b)
Auxiliary Power Unit (APU)
Auxiliary Power Unit (APU)

Overview
Auxiliary Power Unit (APU)

Bearing and Load Compressor

- An Auxiliary Power Unit (APU) is a gas turbine engine.
- An APU will need some form of lubrication (e.g., oil).
- Lubrication needs will be smaller than in aircraft engines, but the APU otherwise experiences the same problems with oil leakage as described for the engine.

APU GTCP36-300
Engineering Design Principles
SAE ARP 1796: Engine Bleed Air Systems for Aircraft  

**Bleed Air Quality:** Requirements should be imposed on the engine manufacturer regarding the quality of the bleed air supplied to occupied compartments.

Under normal operating conditions:
The engine bleed air shall be **free of engine-generated objectionable** odors, irritants, and/or **toxic** of incapacitating foreign **materials**.

Following any type of engine … failure, the engine bleed air shall not contain the above substances to a harmful degree.

… or bleed air systems should incorporate a **bleed air cleaner**.
Engineering Design Principles for Air Conditioning from SAE

**SAE AIR 1168-7: Aerospace Pressurization System Design**
“Compressor bleed from turbine engines is attractive because of the mechanical simplicity of the system.” However, “oil contamination ... can occur in using compressor bleed air from the main engines.” “Popular opinion regarding the risk of obtaining contaminated air from the engine may preclude its use for transport aircraft, regardless of other reasons.”

**SAE AIR 1116: Fluid Properties**
“Until adequate toxicity data are available precautions must be observed in handling any unfamiliar fluid.”

**This means:**
It is not the task of passengers and crew to prove that engine oils and hydraulic fluids as used today are dangerous. Just on the contrary, *industry has to prove that fluids and equipment are safe before they intend to use them*, because standards have been agreed among engineers already long time ago, not to use bleed air on transport aircraft!
Sensors and Filters
Sensors and Filters

**Air Sampler for Later Air Analysis**

Prof. Van Netten invented this "VN-Sampler". It is **not** an in situ measurement device, but a means to collect the air in a fume event for later detailed analysis in a laboratory on the ground. The device is FAA approved.

(Van Netten 2008)
Sensors and Filters

Get Informed => Personal CO Detector. Get Protected in the Cabin => Breathing Mask

Normal CO Situation

• The Carbon Monoxide (CO) level in normal operation is much lower than the limit of 50 ppm (specified in CS 25.831). Failure cases did not occur during these measurements.
• We know much CO is present in the cabin during a Fume Event. The elevated CO concentration indicates the severity of the event. Therefore, crew should carry their personal CO detector and be informed and make decisions accordingly!
• If smoke is present, checklists tell pilots to put on their oxygen mask. In such a case, cabin crew should consider wearing a personal breathing mask protecting against nerve gas.

Failure Case: Fume Event


Get CO Detector and Breathing Mask
Sensors and Filters

Sensors to Detect TCP and VOC

**aerotracer** (Airsense 2017)
- offered for sale.
- detects 15 substances: grease, liquid, gas: engine oils, de-icing fluids, hydraulic fluids, corrosion inhibitors, glue, heat transfer fluid, kerosene, ...
- power supply: 110 to 240 VAC; 30 W or rechargeable battery (operating time 4 hrs).
- electronics: graphical display, Mini SD Card.

**VN Aerotoxic Detection Solutions (VN-ADS)** (Aircraft Interiors 2017)
- prototypes are tested.
- Company claims to have the world’s first real-time detector of poisonous compounds in aircraft cabins.
  (Aircraft Interiors 03/2017)
- Mono Fibre Optical Measuring Technology (MOMT) ... have demonstrated the capability to detect Tricrysel Phosphate (TCP) and other Volatile Organic Compounds (VOCs) and Semi Volatile Organic Compounds (SVOCs) in real time.

**Measurement of hydrocarbon content** (ppm- and ppb-level)

a) Measuring the (unaltered) bleed air from an APU at HAW Hamburg,

b) Checking the sensitivity of the equipment with pyrolyzed aviation fluids.

Gröger und Obst GmbH, 2014. The equipment is still too large (blue rack) for easy integration into the aircraft. See also: Reiss 2016. Smaller version on next page!
Sensors and Filters

**Measurement of Hydrocarbon Content in Air GO-MINI-ATC**

Online analysis system for determination of the THC (Total Hydro Carbon) fraction of the air.

- Power consumption max.: 350 W
- Power supply: 230 V, 50 Hz
- Dimensions (HxWxD): 450mm x 440mm x 320mm
- Weight: 30 kg
- Operating temperature oxidation oven: 1.000 °C
- Temperature rise time: approx. 60 minutes
- T90 time: 10 seconds

(Gröger 2017)
Sensors and Filters

Filters to Remove TCP and VOC

Pall has several treatment solutions for cabin air on offer:
- Carbon Filter
- Photo Catalytic Oxidization (with UV light)
- Catalytic Converters (oxidization). Location is possible:
  - upstream of the pack,
  - downstream of pack,
  - at recirculation filter
  (reduced efficiency compared to a filter in line with the pack – see next page)

Pall offers Odour/VOC Removal Filters
- The carbon adsorbent is effective at adsorbing volatile organic compounds (VOC). Test results have shown a removal efficiency of 65% ... 73% when challenged with TCPs in the gaseous phase. Carbon adsorbents have some effectiveness with ozone but not with carbon monoxide (CO). Removal of these compounds from the cabin air is by adsorption on to carbon based filters. (Pall 2011)

Application of carbon filters:
- 33 HEPA-Carbon filters have been added (so far) to A321 aircraft at Lufthansa Group. (Lufthansa 2017)
- Pall carbon filters are installed on the B757 cargo fleet of DHL. Carbon filters are installed in place of the air ducts leading to the cockpit. EASA issued an STC for the installation. (EASA 2010)
Sensors and Filters

Filter in the Recirculation Path

Example:
- The Pall carbon adsorbent is effective at adsorbing volatile organic compounds with a removal efficiency of 65% ... 73% when challenged with TCPs in the gaseous phase. (Pall 2011)
- The A320 has a recirculation rate of 50%.
- With a filtration rate, $x_{fil} = 0.7$ and a recirculation rate, $x_{re} = 0.5$
- $\Rightarrow$ the filter reduces the incoming concentration to 58.9%.

Adapted from (NRC 2002)
Sensors and Filters

Full Filtration (Option: 1)

- Filtration aft of source (engine / APU). Filtration in recirculation.
- Outflow valve
- 50% recirculation
- Cross bleed valve (normally closed)

\[
\frac{x_{\text{cont, cab}}}{x_{\text{cont, in}}} = (1 - x_{\text{fil}}) \cdot f_{\text{recirc}} \\
\approx 0.3 \cdot 0.6 = 0.18
\]

=> reduces incoming pollutant concentrations to \(\approx 18\%\)

- VOC Filter
- Combined HEPA & VOC Filter (HEPA-Carbon Filter)

Dieter Scholz:
Cabin Air Contamination

59th Congress of the German Respiratory Society

16.03.2018, Slide 57
Aircraft Design and Systems Group (AERO)
Technical Solutions
Technical Solutions

Cabin Pressurization Principles and Solutions

Overview

- **First Jet Aircraft** used a "blower" or "turbocompressor" (TC). The TC is the coupling of a turbine with a compressor. Bleed air from the engine compressor drives the TC turbine. The TCs compressor compresses outside air to meet the pressurization requirements of the cabin. The hot compressed air needs to be cooled. This can be done with a "vapor cycle system" (as known from the refrigerator).
- **Current Aircraft** make use of bleed air directly. It is compressed so much that it contains enough energy to also drive the pack that cool the bleed air down to temperatures considerably less than 0°C.
- The **Boeing 787** uses electrical power to drive an electric motor to drive a compressor. The energy is extracted from the engine by means of shaft power driving a generator. No bleed air is used. The engine is "Bleed Free".

![Diagram of cabin pressurization principles and solutions](image-url)

(Michaelis 2010)
Technical Solutions

Electrical (Bleed Free) Cabin Air Supply

Solution B787!

The "Pack" of the B787's Environmental Control System (ECS) is powered by electric motors (M) to compress ambient air up to cabin pressure and to push the air through the heat exchangers (HX) for cooling. The power for the electric motors is produced by generators (SG) connected to the aircraft's engine and APU. After compression and cooling the air is delivered to the cabin.
Technical Solutions

More Electric A320?

Electrical innovations
flightlab

AIR

GENERATOR

e-PACKS

ELECTRICAL POWER CENTER

eAPU

Aircraft Design and Systems Group (AERO)

Hamburg University of Applied Sciences
Technical Solutions

More Electric A320 with Electrical (Bleed Free) Cabin Air Supply?

The Electrical Environmental Control System (E-ECS) was developed by Liebherr-Aerospace Toulouse SAS, Toulouse (France), Liebherr’s center for air management systems. The E-ECS is equipped with a new type of motorized turbo compressor (50 kW) which enables to use directly external air (bleed less) for air conditioning. The power electronics ensure the speed control of the motorized turbo compressor and offer synergy capabilities with other electrical loads to optimize the overall electrical power consumption on board the aircraft. The interaction between air intake and the turbo-compressors and the performance of the system in all operating conditions was tested in a flight test campaign with Airbus A320-Prototyp MSN001 from June 3 to June 24, 2016. E-ECS will also contribute to fuel burn reduction.

(Liebherr 2016)
Cabin Air Contamination – An Aeronautical Perspective

Summary

• There are many reasons for aircraft cabin air contamination. Important:
  engine oil, hydraulic fluid, anti-icing fluid – chemically altered at high temperatures
  (=> different chemicals than expected, causing different symptoms)

• Engine seals leak a small amount of oil by design =>
  continuous low dose contamination in (almost) all jet aircraft

• Fume Events could be called better Cabin Air Contamination Events (CACE) =>
  occasional high dose contamination

• Crew should not use their nose as sensor. Instead: use low-cost CO sensors

• Demand technical changes: filter for retrofit and
  bleed-free architecture for newly designed aircraft
Cabin Air Contamination – An Aeronautical Perspective

Contact

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http://www.ProfScholz.de

http://CabinAir.ProfScholz.de
Cabin Air Contamination – An Aeronautical Perspective

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